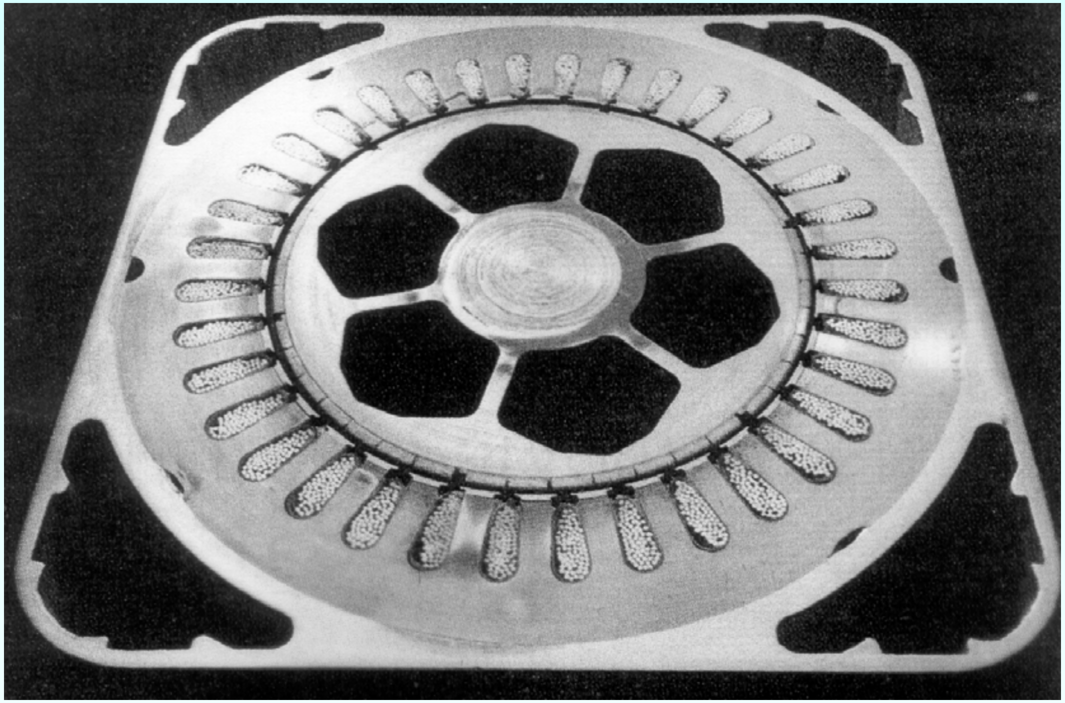
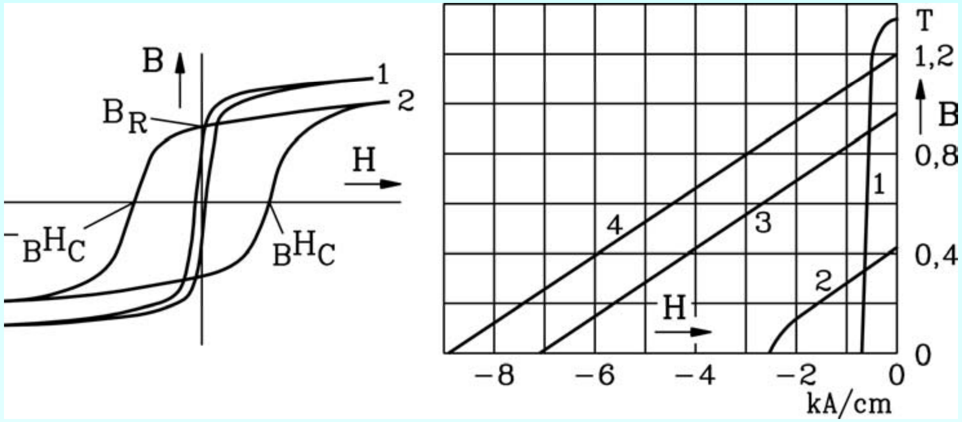
8. Permanent magnet synchronous machines



Source:

Siemens AG, Germany

Permanent magnet materials



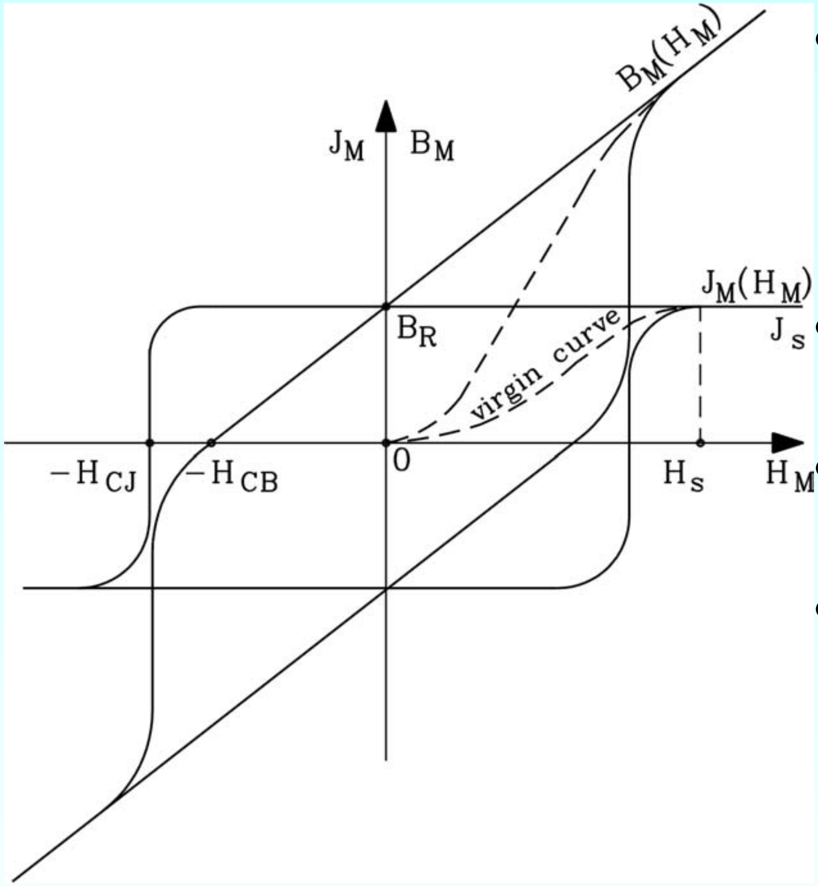
- B_R: **Remanence flux density**
- ${}_BH_C$: **Coercive field strength of *B(H)*-loop**
- **Material data *B(H)*:** static "hysteresis"-loop (here: at 20° C)

- **Soft magnetic materials (1):** Iron, nickel, cobalt: B_R and ${}_BH_C$ are small: Application in magnetic AC fields
- **Hard magnetic materials (2):** = Permanent magnet materials: B_R and ${}_BH_C$ big: Application for generation of magneto-static fields

1. **Aluminium-Nickel-Cobalt-Magnets** (Al-Ni-Co) high B_R, low ${}_BH_C$, cheap
2. **Ferrite** (e.g.. Barium-Ferrite) rather low B_R, but increased ${}_BH_C$
3. **Rare-Earth Magnets** Samarium-Cobalt: high B_R & ${}_BH_c$, small influence of temperature
4. **Rare-Earth Magnets** Neodymium-Iron-Boron: very high B_R & ${}_BH_C$, decreasing with increasing temperature

- Magnetic point of operation of PM: **in 2. quadrant of *B(H)*-loop**

Rare-earth magnets: Linear *B(H)*-Curve in 2. quadrant



- Self-field of permanent magnets is called **magnetic polarization J_M**, which adds to the external field H_M, yielding the resulting flux density B_M:

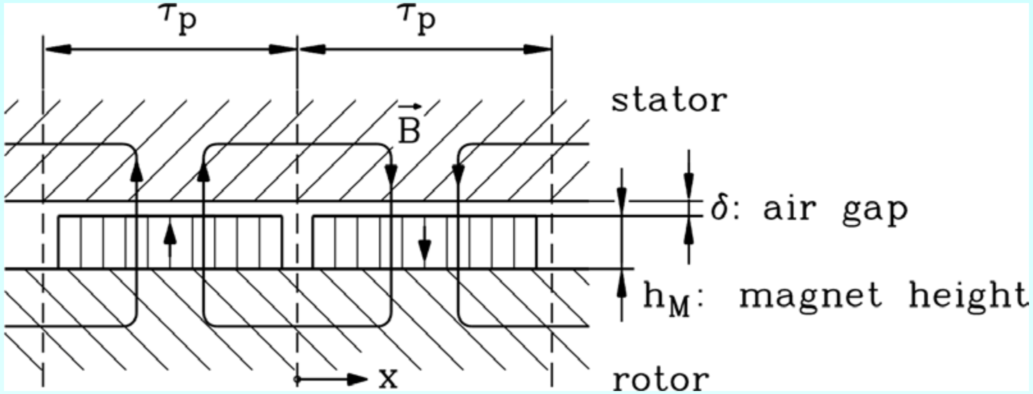
$$\vec{B}_M = \mu_0 \vec{H}_M + \vec{J}_M$$

- Rare-earth magnets are developed for high saturation polarization J_s .
- After turn-off of external field the **remanence flux density** $B_R = J_M(H_M = 0) = J_R$ remains.
- Two **coercive field strengths** H_C defined:
  a) At $-H_{CB}$ the resulting magnetic flux density B_M is zero.
  b) At $-H_{CJ}$ the magnetic polarization J_M within the magnet is zero.

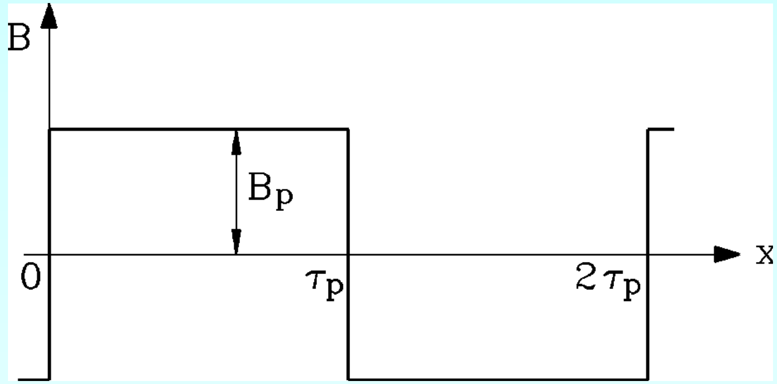
$B_M(H_M)$-loop results from adding the $J_M(H_M)$-loop and the straight line $B_M = \mu_0 H_M$. Hence it is **nearly linear** in the 2nd quadrant **:**

$$B_M = B_R + \mu_M H_M, \quad \mu_M = ca.1.05\mu_0$$

PM synchronous machines: Air gap flux density B_p



PM rotor with surface mounted magnets



Air-gap flux density distribution at no-load (I_s = 0)

- No-load air gap flux-density B_p: Approximation $\mu_M = \mu_0,\ B_M \cong B_R + \mu_0 H_M$ and $\mu_{Fe} \to \infty$.

- *AMPERE´ s law gives:* No-load ($I_s = 0$) = electrical *Ampere* turns Θ are zero;

$$2(H_\delta \delta + H_M h_M) = \Theta = 0$$

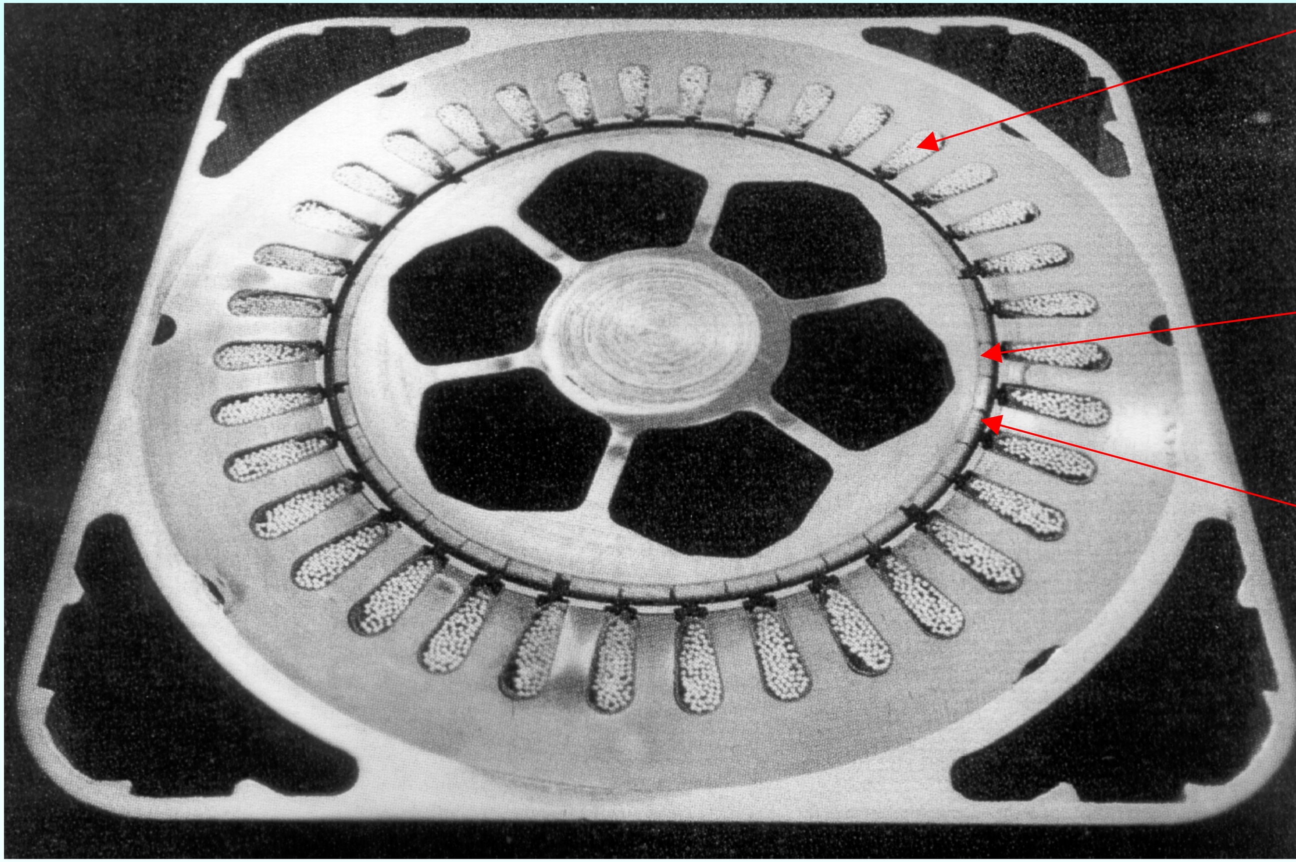
- Constancy of flux between field lines $\Phi = B_M A_M = B_\delta A_\delta$

- Identical cross section areas $A_M = A_\delta$ in magnets and in air-gap give: $B_M = B_\delta$

$$B_p = B_\delta = \mu_0 H_\delta = \underline{\underline{-\mu_0 \frac{h_M}{\delta} H_M}} = B_M$$

magnetic operational line $B_M(H_M)$

Small 6-pole permanent magnet synchronous machine with surface mounted magnets



Stator slots with single layer winding, round wire

q_s = 2 coils per pole and phase

Rotor rare earth permanent magnets, 7 magnet pieces per pole in circumference

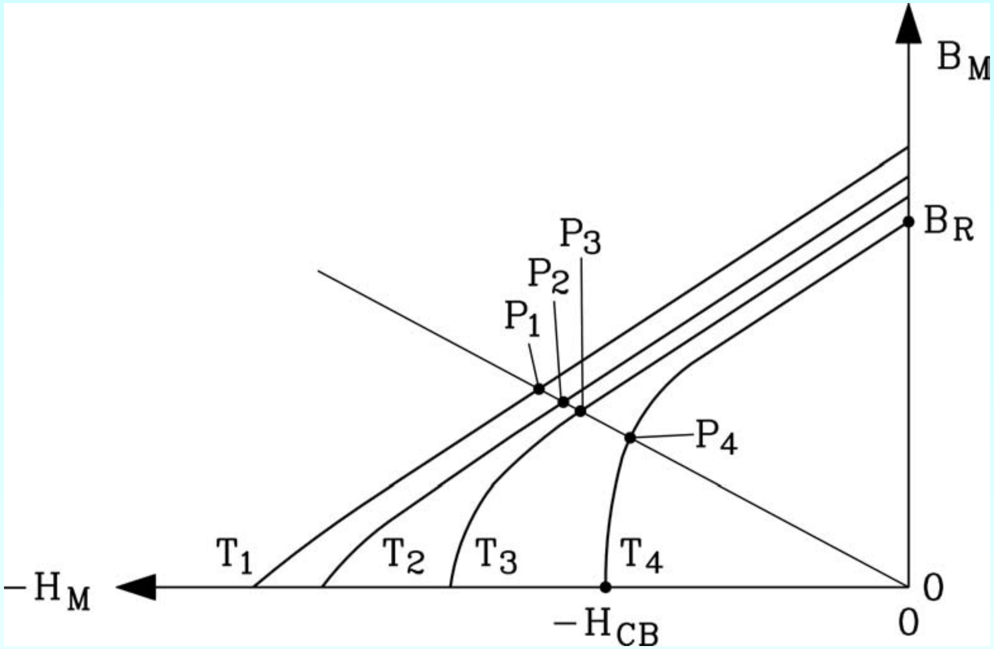
glass fibre bandage for fixation

95% pole coverage

Source:

Siemens AG, Germany

PM synchronous machine: Magnetic point of operation *P*

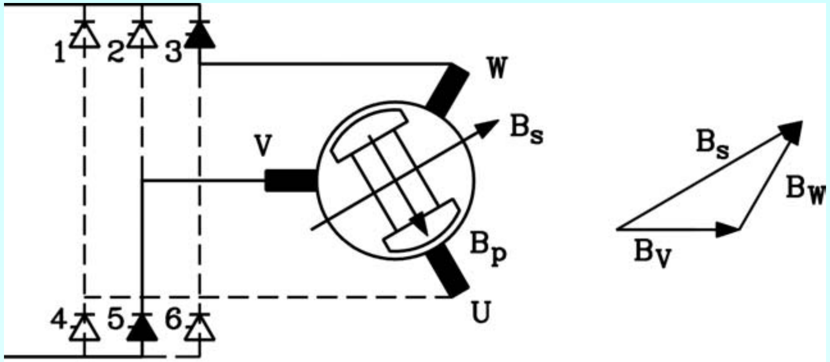


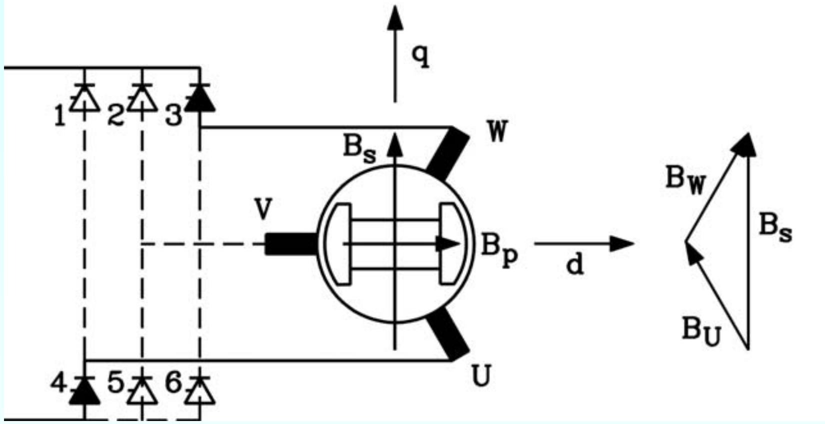
- **Determination of magnetic point of operation *P*:**
  Intersection of **magnetic line of operation** and of $B_M(H_M)$-loop of PM material:
  Intersection point is *P* !
- **Temperature influence *T*:**
  $B_M(H_M)$- loop of material depends on T.
  With increasing temperature the magnetic flux decreases:
  Temperatures $T_1 < T_2 < T_3 < T_4$.

- At rotors with surface mounted permanent magnets the air gap flux density B_p is always **LOWER** than the remanence flux density B_R (the lower, the bigger the ratio "Air gap width / magnet height" is).

- Due to $\mu_M \cong \mu_0$ the stator magnetizing reactance for *d*- and *q*-axis is the same, if iron saturation is neglected: $X_d = X_q$. So, PM-machine with surface mounted magnets **may be regarded as round-rotor machine**.

Inverter operation - rotor position control





$$M_e = \frac{m_s}{\Omega_{syn}} \cdot \left(U_p \cdot I_{sq} + (X_d - X_q) \cdot I_{sd} \cdot I_{sq} \right)$$

- Depending on rotor position, the stator winding is fed with three-phase current system so, that stator field has always **a fixed relative position** to rotor field. Measurement of rotor position with e. g. **incremental encoder** or **resolver**. Rotor cannot be pulled out of synchronism, as stator field is always adjusted to rotor position.
- *Often used control method* with PM-drives: Stator current is fed as pure q-current:

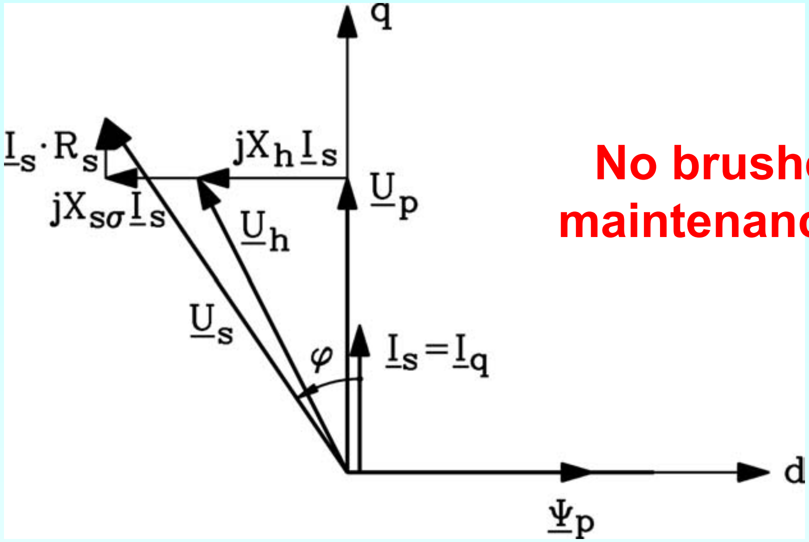
$$I_s = I_{sq}, I_{sd} = 0$$

Result: Stator field axis B_s is perpendicular to rotor field axis B_p.

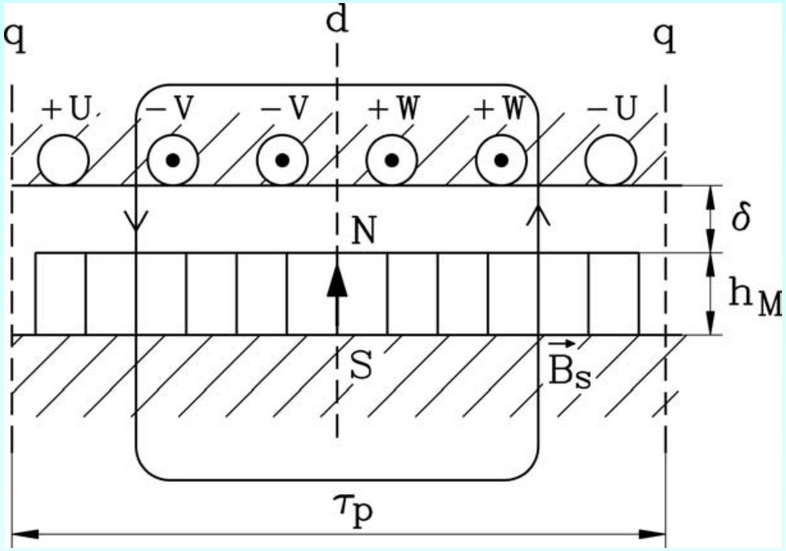
Torque for a given stator current I_s is maximum, because at $L_d = L_q$ only I_{sq} will produce torque with rotor field.

$$M_e = m_s \cdot U_p \cdot I_{sq} / \Omega_{syn}$$ or with $U_p = \omega_s \Psi_p / \sqrt{2}$: $$M_e = p \cdot m_s \cdot \Psi_p \cdot I_{sq} / \sqrt{2}$$

PM synchronous machine as "Brushless-DC" - drive



No brushes: Low maintenance costs !



- At I_{sq}-operation I_s and U_p are in phase. All current-carrying conductors of same current flow direction are positioned in rotor field of the same polarity. So the *LORENTZ*-forces on all conductors coincide in tangential direction like in DC machines.
- For $R_s \cong 0$ we get from phasor diagram : $U_s = \omega_s \sqrt{L_q^2 I_{sq}^2 + (\Psi_p / \sqrt{2})^2}$

  Control law for inverter (like in induction machines): $U_s \sim \omega_s$

- Torque: $M_e \sim \Phi_p \cdot I_s$ in DC machines similar: $M_e \sim \Phi \cdot I_a$

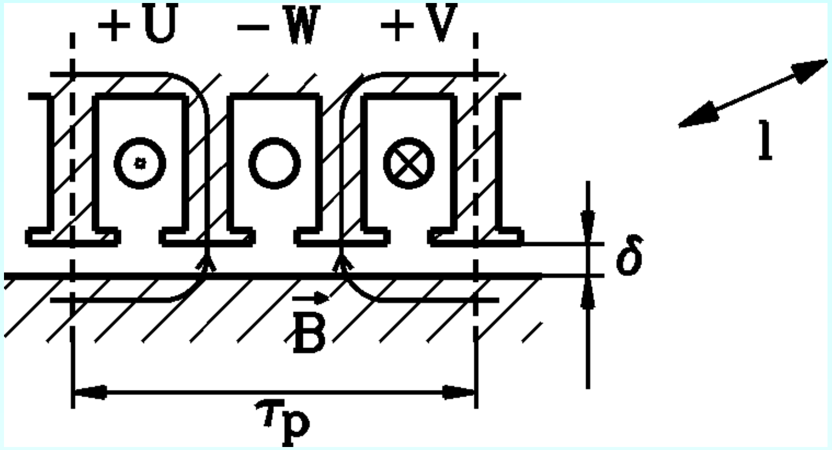
DC machine: *commutator + brushes* *rotor armature winding* *stator main poles*

"brushless DC" -drive: *inverter + encoder* *stator winding* *rotor poles*

Direct drive wind turbine generators

- Gearless drive demands low speed, but high torque
- High torque demands big rotor diameter
- Low speed demands low frequency and high pole count $n = f_s/p$
- Too high pole count gives very small rotor poles with very fine stator slotting: very expensive
- So stator side inverter is used to reduce stator frequency
- Big diameter and high pole count not good for induction machine design: too high magnetizing current
- Preferred: synchronous machines. With PM excitation reduction in losses possible.

High pole count induction machine: Big magnetizing current



- Magnetizing current $I_m \sim U/(2\pi L_s) \sim \delta/\tau_p$
  Phase inductance $L_s = L_{s\sigma} + L_h$ $\quad L_h \sim l \cdot \tau_p/\delta$
- (a) High pole count: $2p$ big $\Rightarrow$ Pole pitch $\tau_p = d\pi/(2p)$ small
  (b) Mechanical lower limit for air gap δ given $\Rightarrow$ *τ_p/δ small, leads to small L_s*

	P/kW	n/min^{-1}	f/Hz	$2p$	d/m	τ_p/mm	δ/mm	δ/d /%	τ_p/δ	l/m	$\cos\varphi$	I_m/I_N
I	750	28	22.4	96	5	164	5	0.1	32.8	0.35	0.6	0.8
II	640	1514	50	4	0.45	353	2	0.4	176.5	0.66	0.91	0.27

I: High pole count direct drive with induction machine

II: Geared drive with induction machine frame size 400mm, transmission i = 50

High pole count synchronous machine, electrically excited

- Rotor: DC excitation allows over-excited operation, e.g. $\cos\varphi = 0.8$ for inductive load.
- BUT: Necessary Ampere turns increase linear with pole count.

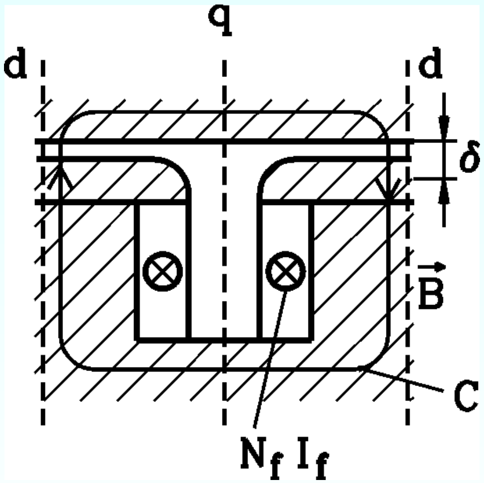
  Demand: Torque is determined by air gap field B_δ and stator current. Stator current is limited by cooling due to stator winding losses, so B_δ should be about 0.8 ... 0.9 T.

  According to *Ampere´s* law (for closed loop C) we get $B_\delta = \mu_0 N_f I_f / \delta$ independently of pole count $2p$

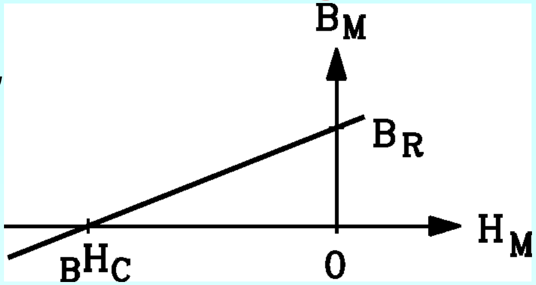
  ($N_{f,pole} I_f = \Theta_f$: Ampere turns per pole, $N_{f,pole}$: number of turns per coil per pole, I_f : DC exciting current).

  $\Rightarrow$ Excitation losses $P_f = 2pP_{f,Pol} \sim 2p \cdot \Theta_f^2$ increase proportional with pole count $2p$

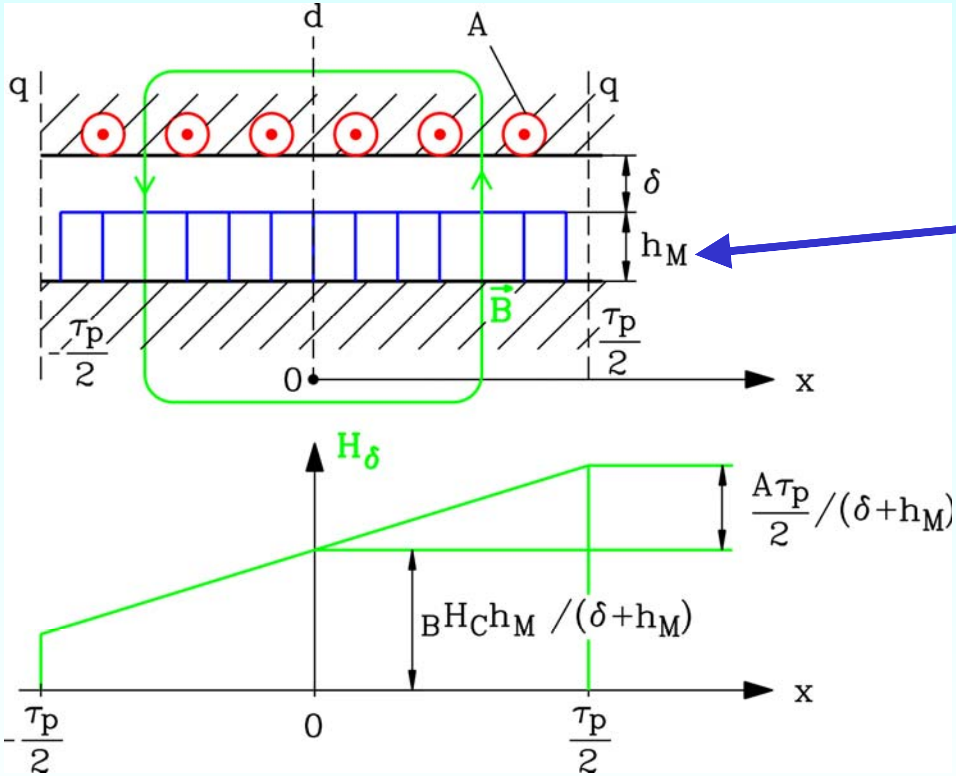
  $\Rightarrow$ **Permanent magnets allow reduction of total losses by avoiding P_f**



Demagnetization limit of surface mounted permanent magnets



- *Ampere´s law*: Closed loop C: $H_M \cdot h_M + H_\delta \cdot \delta - A \cdot x = 0$,
  with $B_\delta = B_M$ and $B_M = \mu_0 ({}_BH_C + H_M)$ we get
  $\Rightarrow \quad H_\delta(x) = ({}_BH_C \cdot h_M + A \cdot x)/(h_M + \delta)$
- No danger of demagnetization, if $H_\delta((x = \tau_p/2) > 0$: ${}_BH_C \cdot h_M > A \cdot \tau_p/2$



Surface mounted magnets, glued to rotor

High pole count leads to low ´ ” active” masses

- *Example:* Comparison at identical pole shape for pole count $2p$ and DOUBLE pole count $2p' = 2 \cdot (2p)$:
  - identical cross section of stator And rotor geometry per pole,
  - hence: identical winding overhang length l_b, (l_b/l_{Fe} = 0.2 at $2p$)
  - identical rating: power P, torque M, n, U, I, air gap flux density B_δ, current density J.

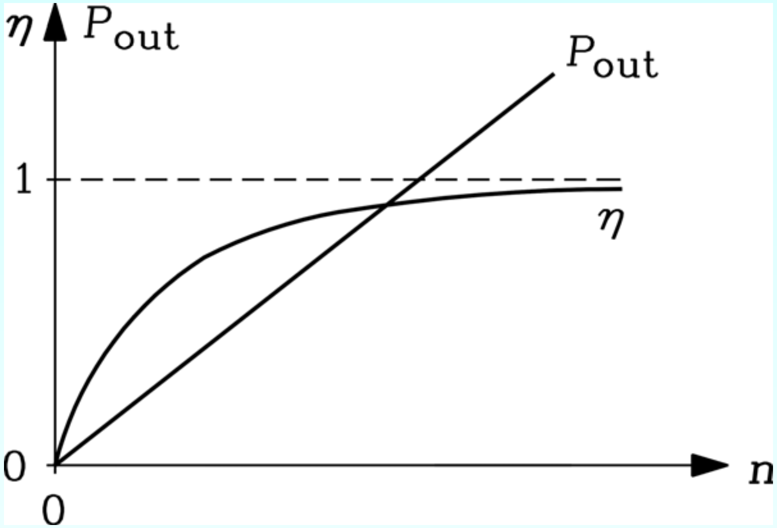
Pole count $2p$	$2p' = 2 \cdot 2p$	$2p$
Stator bore diameter $d = 2p\tau_p/\pi$	200%	100%
Stack length l_{Fe}	25%	100%
Stator frequency $f = p \cdot n$	200%	100%
Stator iron mass of stack $m_{Fe} \sim d \cdot l$	50%	100%
Stator winding mass $m_{Cu} \sim (l_{Fe} + l_b) \cdot 2p$	75%	100%
Magnet mass $m_M \sim h_M \cdot d \cdot l_{Fe}$	>50% *)	100%
Winding losses $3RI^2 \sim m_{Cu}$	75%	100%
Stator iron losses $P_{Fe} \sim f^{1.8} \cdot B^2$	350%	100%

*) Due to increased pole leakage flux ca. 65% for identical pole flux in air gap

- **High pole count leads to reduced active masses, but needs:**
- - low loss iron sheets

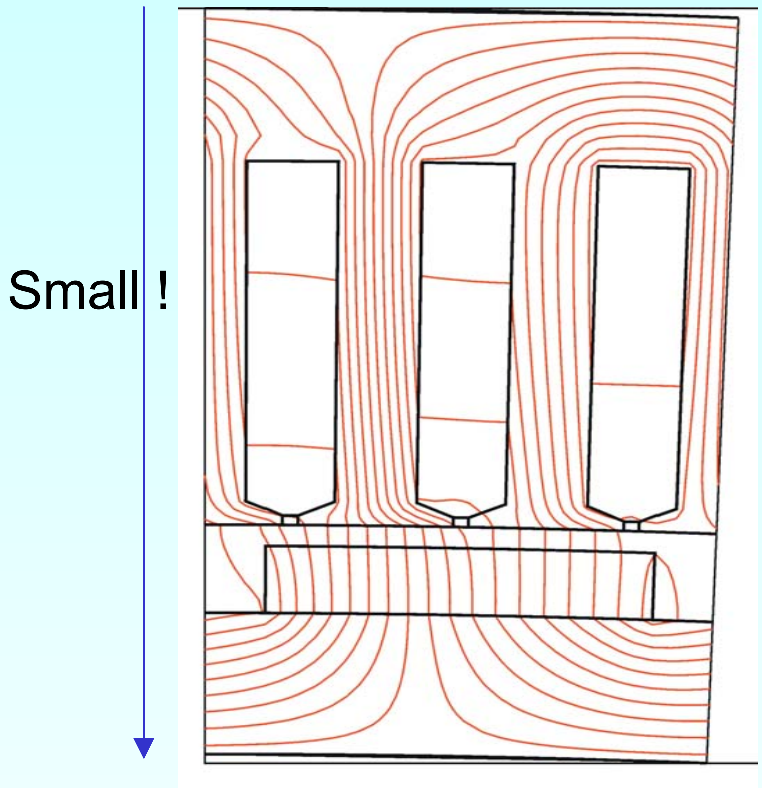
Direct drive PM generator - high efficiency ?

- At given torque *M* the efficiency increases at dominant I^2R-losses with speed *n*.
- Because: Torque $M \sim N_s \cdot I_s \cdot B_\delta \cdot d^2 \cdot l_{Fe} \sim p \cdot \Phi I$ = "Flux x Current"
  Efficiency $\eta = P_{out}/P_{in} \approx 2\pi nM / (2\pi nM + 3RI^2)$



- But: Gear losses reduce efficiency
  Example: Wind converter unit
  (a) Geared induction generaotor: 640 kW, $2p = 4$, 1514/min: $\eta_{Gen} = 96.6\%$
  Gear $i = 50$ (2 stages): $\eta_{Gear} = 97.0\%$ $\Rightarrow \eta = \eta_{Gen}\eta_{Gear} = 93.7\%$
  (b) Direkt drive: 750 kW – permanent magnet synchronous generator: $\eta_{Gen} = 95.3\ \%$
- Result: With PM generator also at low speed good efficiency possible.

Gearless high pole count wind generator



1.5 MW-wind generator:

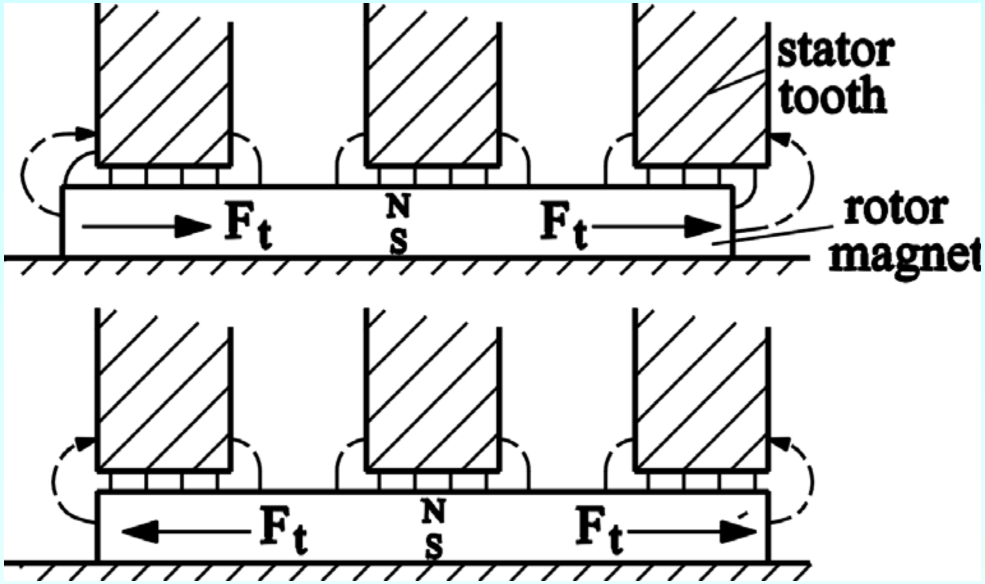
Numerically evaluated total magnetic field per pole pitch at rated data: 1320 A, 690 V, cosphi = 0.85

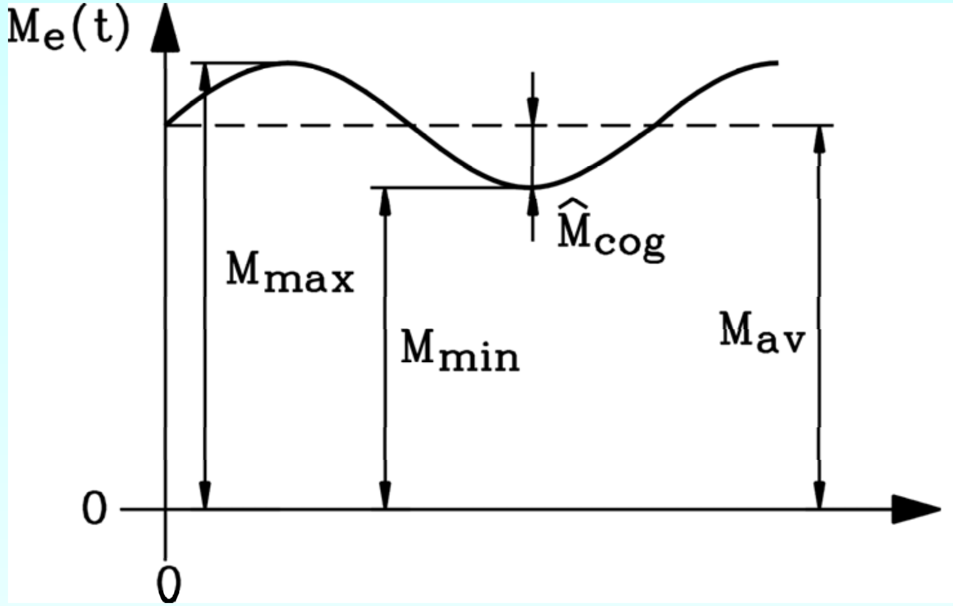
Comparison to electrically excited synchronous generator with high pole count:

-Permanent magnets avoid excitation losses: efficiency increases, temperature level decreases, exciter feeding converter not needed, so in spite of expensive permanent magnets (ca. 40 Euro / kg) still an interesting aleternative

- BUT: Danger of de-magnetization due to stator magnetic field at overload. This must be avoided by deliberate generator design (e.g. at sudden short circuit).

Cogging torque in Permanent Magnet Synchronous Machines





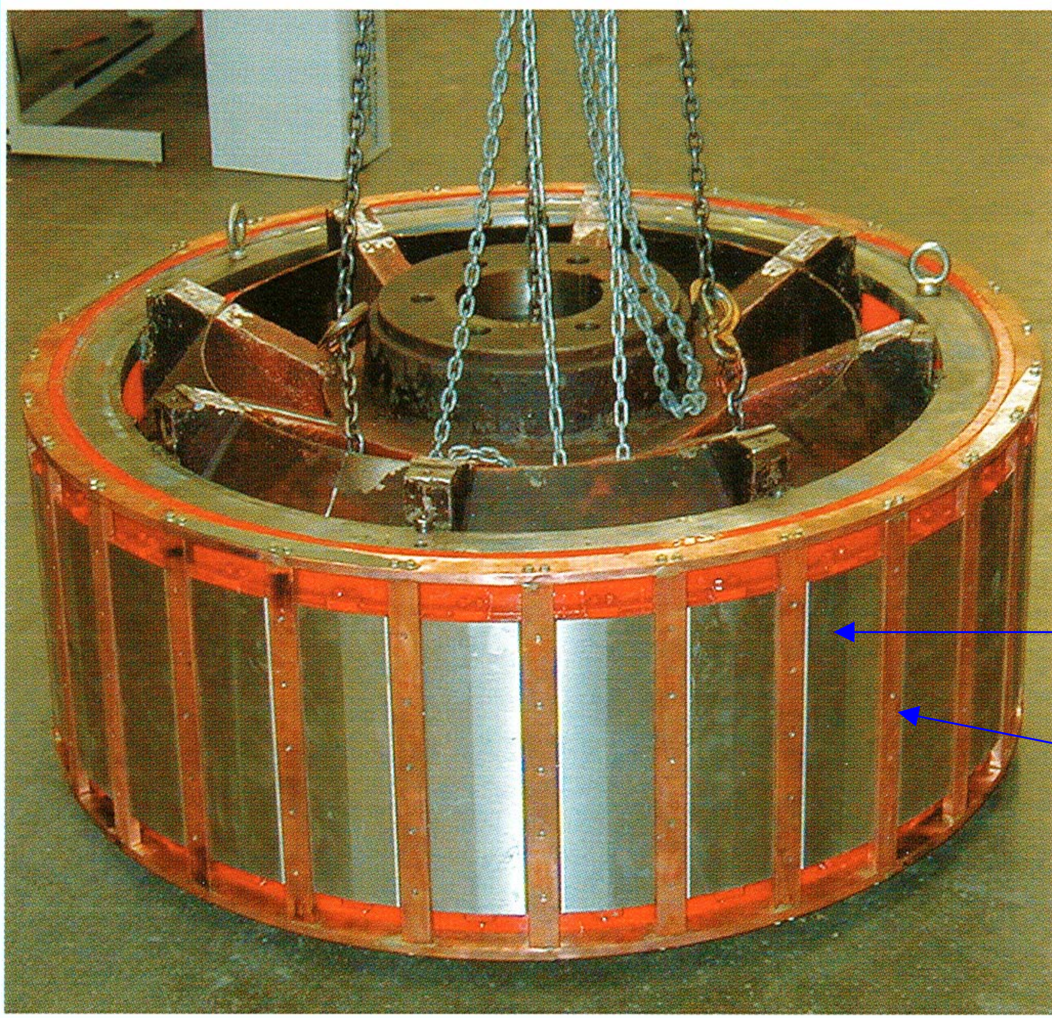
Left: No-load ($i_s = 0$):

above: unaligned position: rotor tangential magnetic pull F_t on stator tooth sides generates no-load cogging torque,

below: aligned position: sum $F_t = 0$, no cogging torque

Right: Load cogging torque as function of time, quantification of torque ripple from measured torque time function (e.g. measured with strain gauge torque-meter)

Permanent magnet rotor of synchronous hydro generator, 24 poles, 250/min



Design for direct grid operation

Small bulb type hydro generator for river power plant

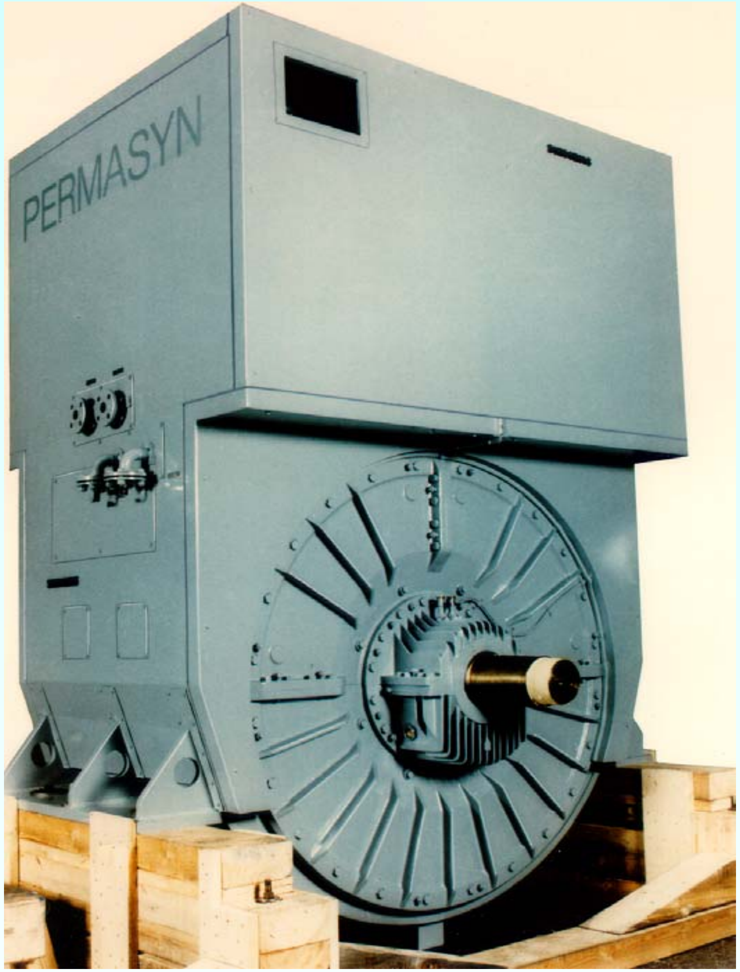
Pole face with magnets

Damper cage

Source:

VATech Hydro, Austria

First Permanent Magnet Motor built in1987



Nominal Power: 1.100 kW
Nominal Speed: 230 / min

- Converter integrated into the upper motor housing.

- Motor built as drive for submarine.

- Surface mounted magnets.

- Oil cooled sleeve bearings.

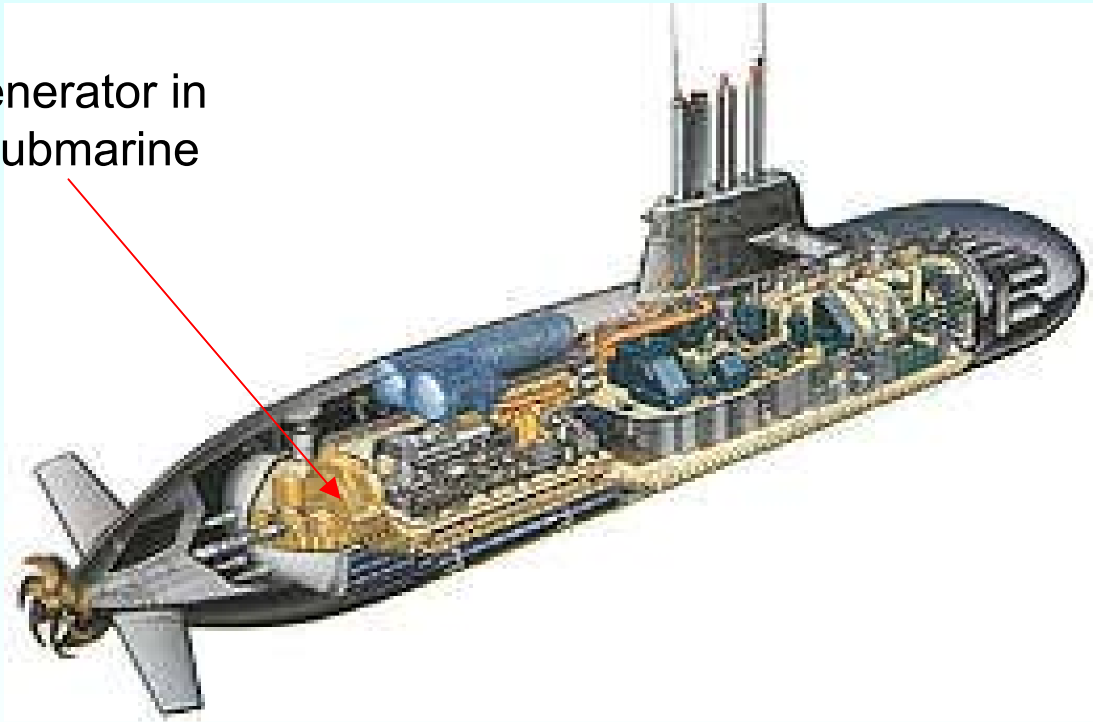
- Top mounted heat exchanger.

Source:

Siemens AG, Germany

„Permasyn " Permanent Magnet Motor for Class 212 of fuell cell powered submarines of HDW ship yard/Germany for German and Italian Navy

PM Motor/Generator in backside of submarine

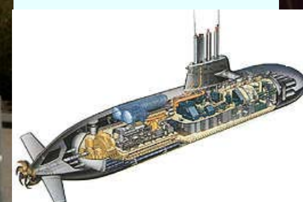


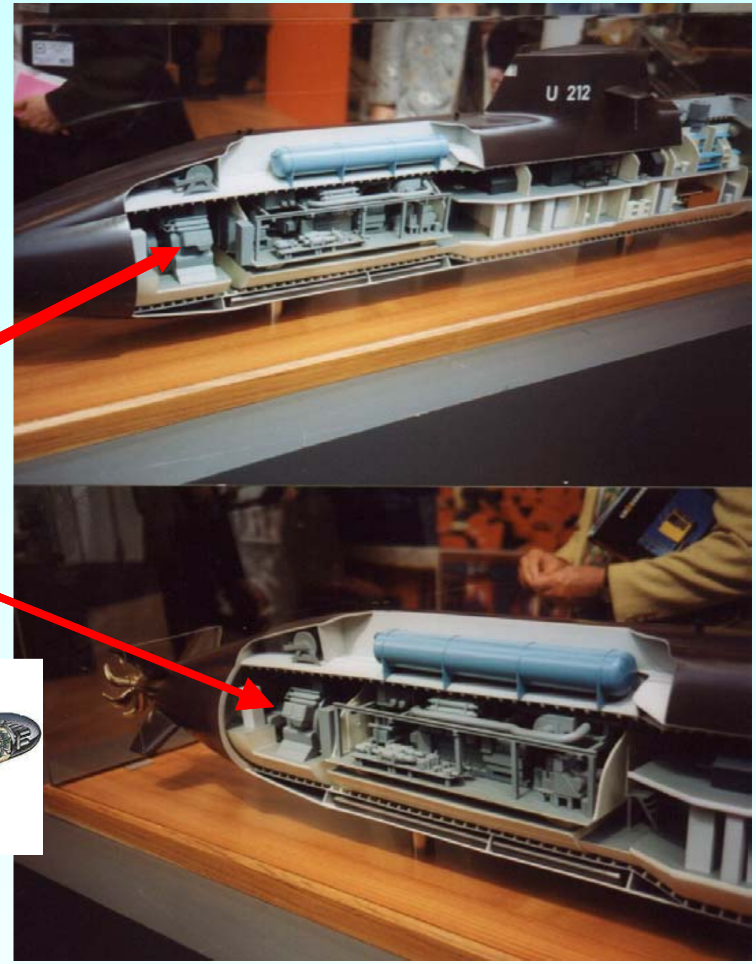
Source:

Siemens AG, Germany

Permasyn-Motor for Class 212

for German and Italian Navy

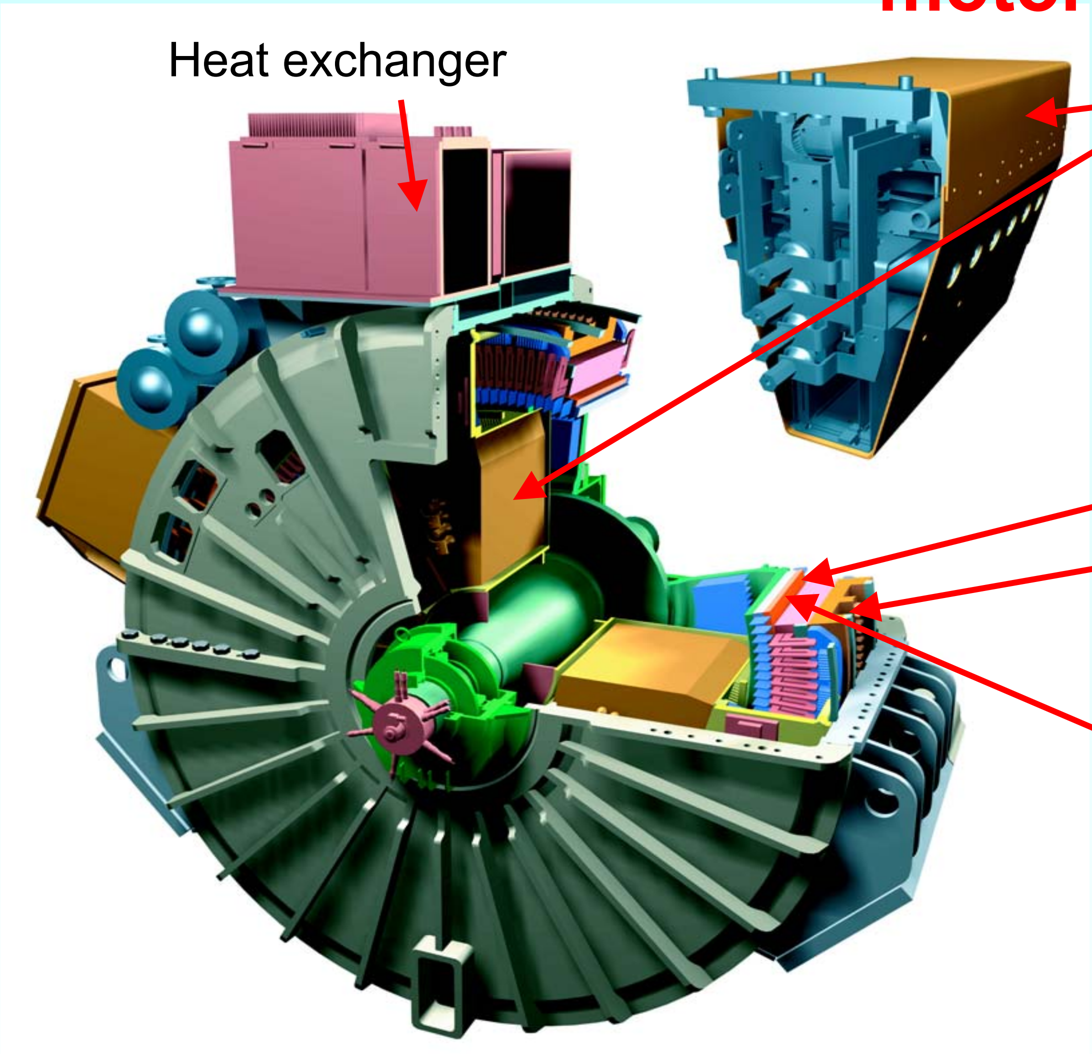




Source:

Siemens AG, Germany

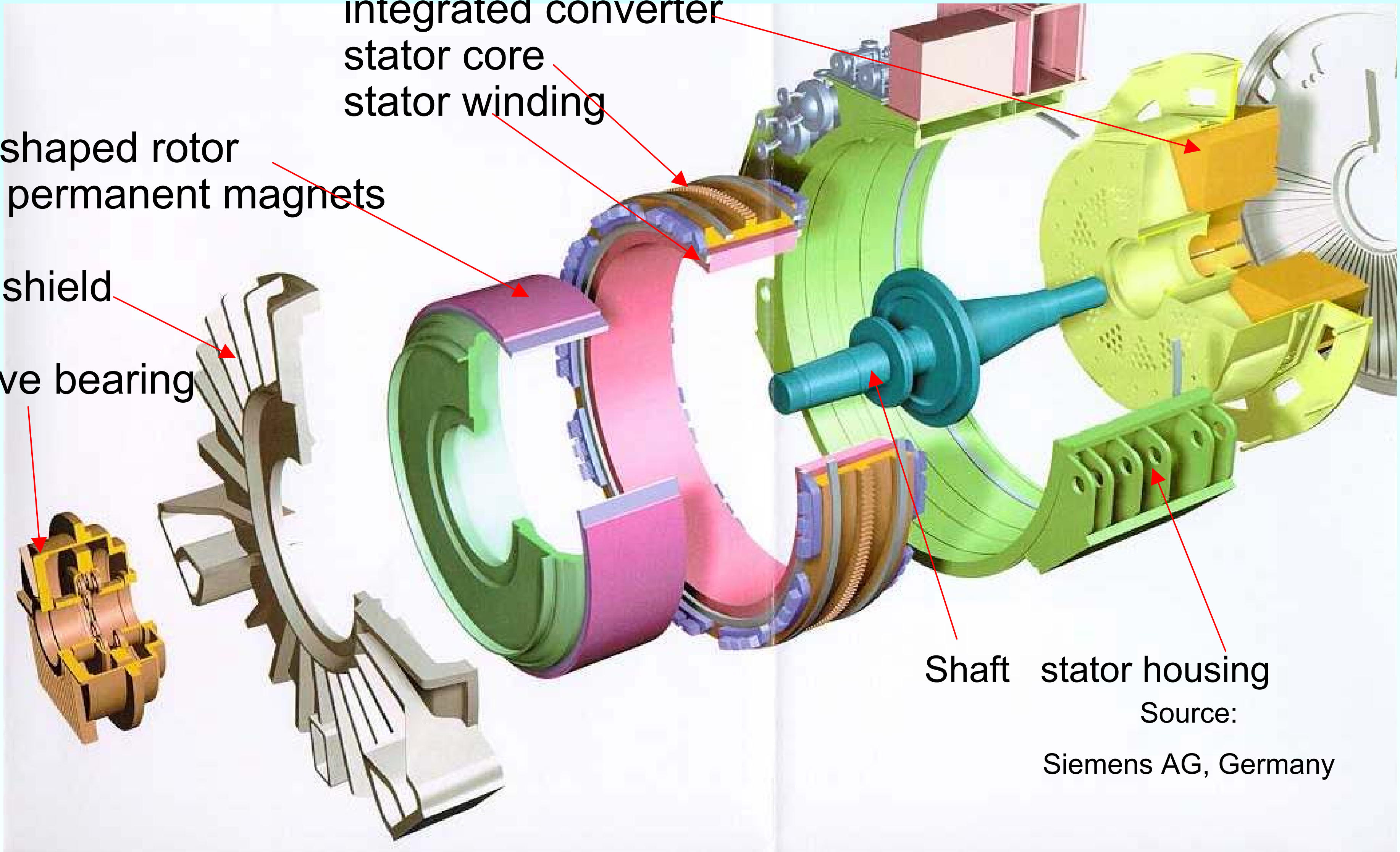
Design of permanent magnet synchronous motor



Source:

Siemens AG, Germany

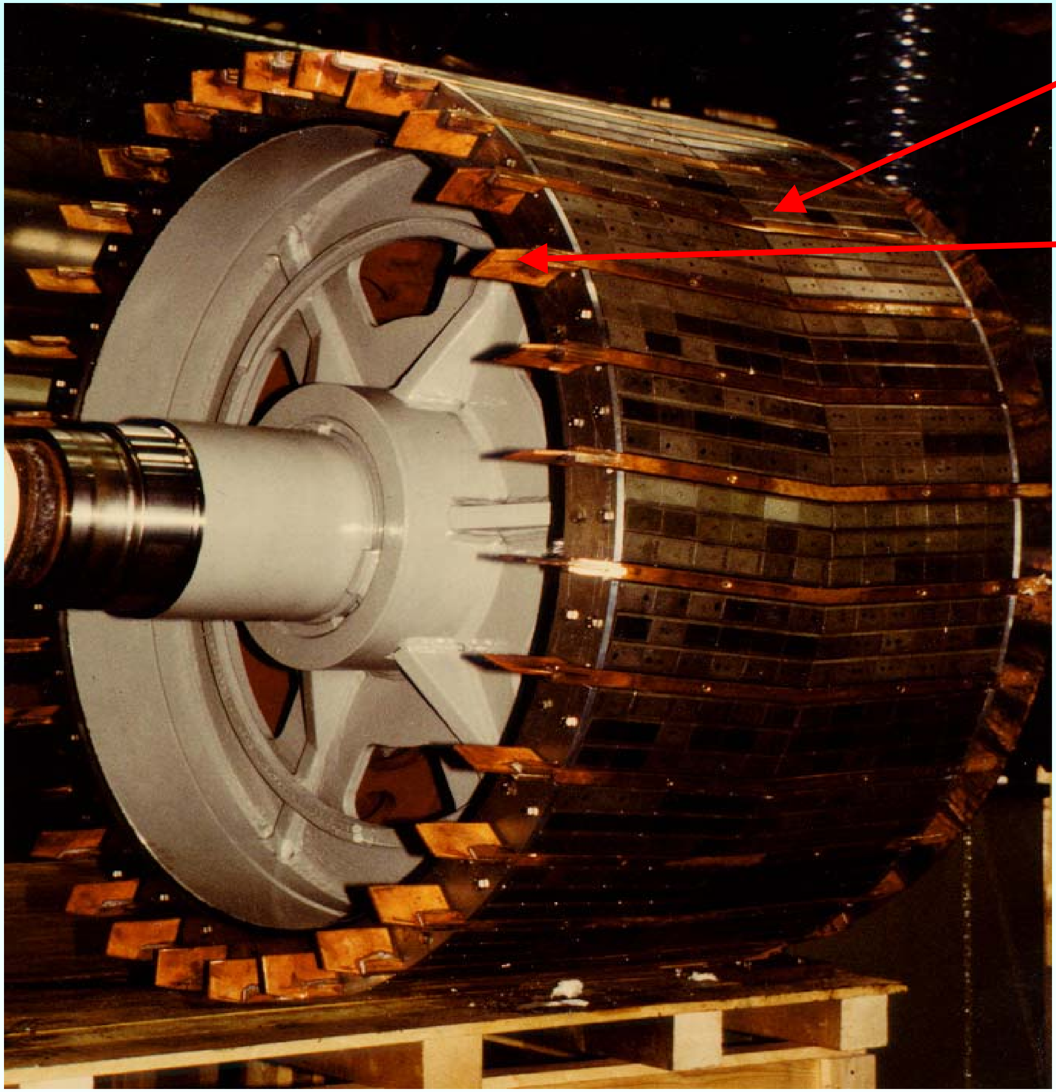
Design of permanent magnet synchronous motor



Source:

Siemens AG, Germany

Rotor of first built Permanent Magnet Synchronous Motor



Skewed rotor magnets to reduce cogging torque

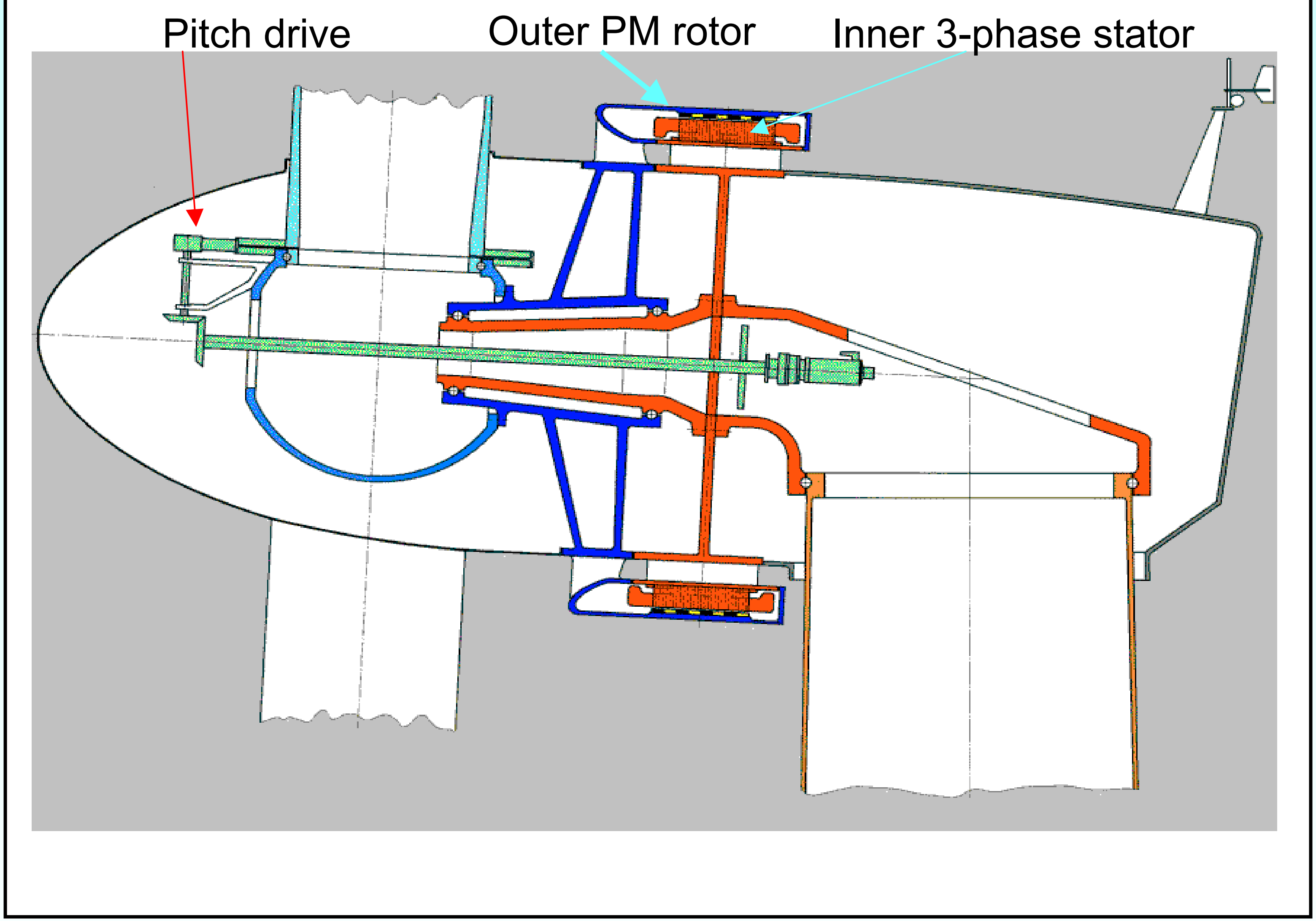
Cooling fins to dissipate rotor magnet eddy current losses and to enhance internal air flow

High pole count (32 poles) for slow speed operation

Source:

Siemens AG, Germany

Permanent magnet outer rotor wind generator



Generator project Vensys 1.2 MW

690 V rated voltage

Grid side IGBT-Inverter

Source:

Innowind, Germany

Goldwind, Urumqi

Xinjiang, China

Permanent magnet wind generator: inner stator

Design for direct coupling to wind turbine without gear

21 / min rated speed

1.2 MW

690 V rated voltage

Grid side IGBT-Inverter

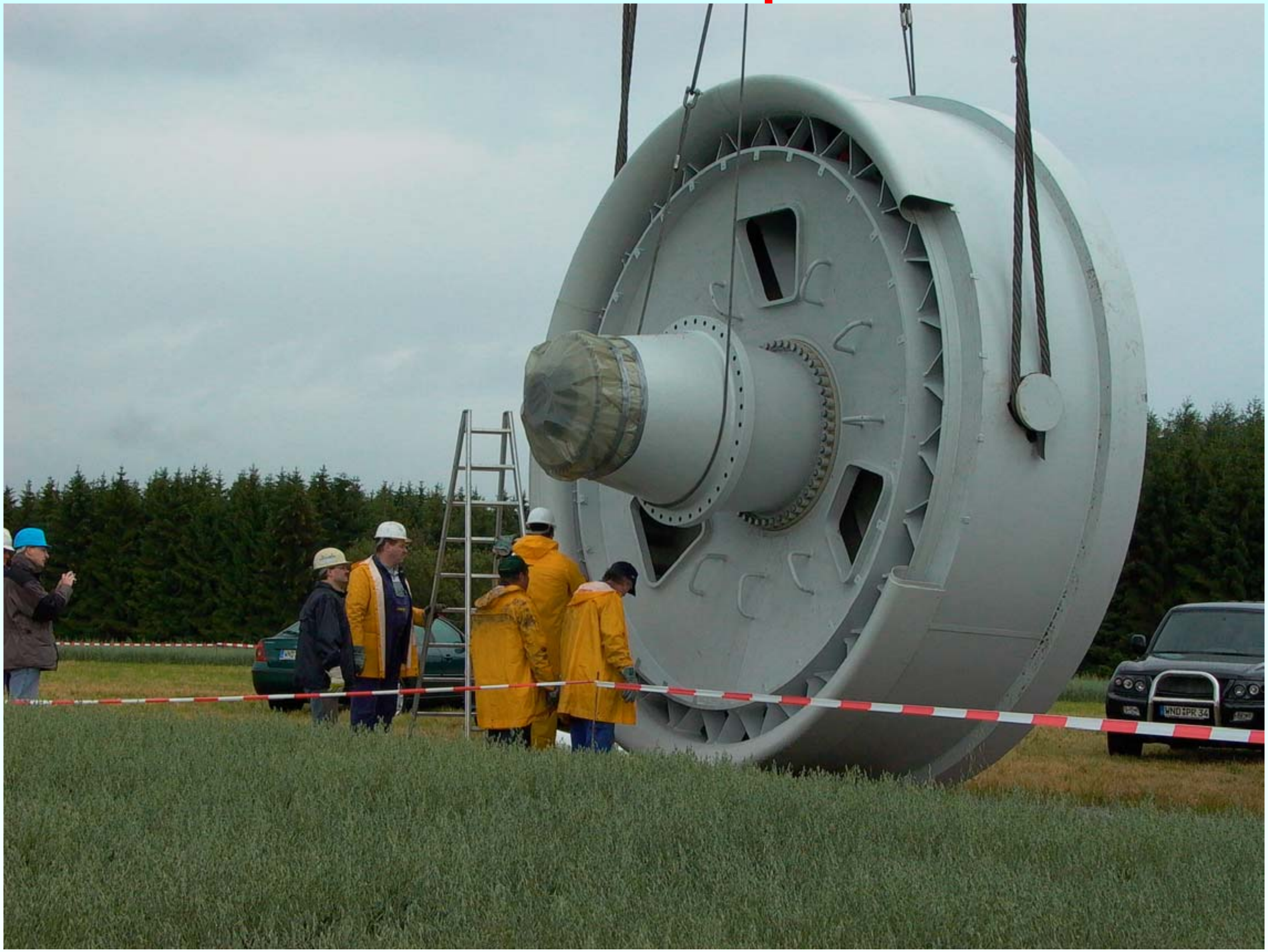
Generator side: Diode rectifier and step-up converter

Source:

Innowind, Germany

Goldwind, Urumqi, Xinjiang, China

Transportation of 1.2 MW permanent magnet wind generator to plant site



Outer PM rotor to increase torque by increased bore diameter

Inner stator with 3-phase winding, operated by inverter

Source:

Innowind, Germany

Goldwind, Urumqi

Xinjiang, China

Mounting of permanent magnet wind generator onto nacelle

Centre pole height 69 m

Steel pole mass 96 t

Wind rotor diameter 62 m

Speed 21 /min

Source:

Innowind, Germany

Goldwind, Urumqi

Xinjiang, China

Permanent magnet wind generator: Mounting of 3 blade wind rotor

1.2 MW turbine

wind rotor diameter 62 m

pole height 69 m

speed 21/min

pitch control

electrical pitch drives

Nacelle and rotor mass: 81 t

Source:

Innowind, Germany

Goldwind, Urumqi

Xinjiang, China

1.2 MW gearless permanent magnet wind generator in operation

1.2 MW turbine

wind rotor diameter 62 m

pole height 69 m

speed 21/min

pitch control

electrical pitch drives

Nacelle and rotor mass: 81 t

Centre pole mass: 96 t

PM generator

Source:

Innowind, Germany

Goldwind, Urumqi, Xinjiang, China